

Studying Material Damping Levels at Cryogenic Temperatures

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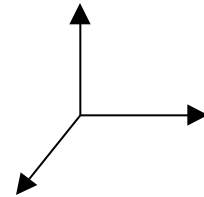
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MOTIVATION

- NGST OTA and Isolation Truss will be operating at cryogenic temperatures (30-60°K) and a low ($<10^{-6}$) strain disturbance environment.
- Modeling group needs information on structural properties at those temperatures:
 - material properties: modulus, CTE, thermal conductivity, thermal diffusivity,
 - dynamic properties: damping, frequencies, hysteresis,
- Zener model predicts damping linear dependency on temperature, and other properties (strain, modulus, ...).
 - First cut estimate would predict near zero damping at cryo temperature and low strain
 - Zener model not proven to be valid for those temperatures
 - Zener model not valid for all classes of materials (e.g., composites) and friction (e.g., microdynamics)
- Extensive literature survey results:
 - insufficient / inconclusive data set
 - materials tested to date of limited relevance to NGST
 - poorly documented test procedures and specimen size

OBJECTIVE

- Test materials and mechanisms which are specific to NGST needs:
 - Al, Be, -Alumina, GFRP, CRFP, mechanisms, joints, latches, ..
- Measure dynamic properties of materials and sub-structures which can be directly applicable to NGST models (other properties to be evaluated by J. Lawrence)
 - (damping, frequency, hysteresis, ...) vs. temp. (JPL)
 - (damping, frequency, hysteresis, ...) vs. strain (ROSI & CU)
 - (damping, frequency, hysteresis, ...) vs. gravity (IPEX, CU & ???)
- Initially use experimental data to evaluate *trends* of damping vs. temperature for classes of materials (metals, ceramics, composites) and mechanisms. Then (if necessary) correlate to models.
- Develop unified test protocols which can be used for benchmark testing of further materials, mechanisms, and structural elements through the end of the project (and beyond - TPF)
- Start by testing samples of materials, and then progressively build-up size and complexity of test articles.
- Go beyond just measuring damping and frequencies. Use this facility/data for FEM model correlation at cryo temperature (e.g., physical parameter updating)



APPROACH

- Use existing facilities and capabilities to minimize cost and schedule.
- Use the ROSI Microdynamic strut tester to evaluate dynamic properties at low strain:
 - Microdynamic tester already exists and is a cost-effective facility at room temperature
 - Use same samples at the ROSI and JPL facilities to have full description of the properties as a function of temperature and strain.
 - Perform tests at ROSI and JPL which would overlap each other for calibration
 - Propose ROSI / CU facility for larger test articles (e.g. built-up elements of NGST)
- Develop new test set-up at JPL for small NGST components and materials:
 - Unlimited use (to within other project needs) of 2 thermal vacuum chambers (24in.& 36in.- with cryogenic capability down to 10°K
 - Cryogenic testing expertise and equipment within my JPL current group
 - Minimal cost of use
 - Collaborate with CU for microdynamic testing expertise
 - ROSI facility currently not capable below 100°K, and more expensive

WHAT IS DAMPING?

- NGST modelers are seeking the EQUIVALENT MODAL DAMPING (a.k.a.:) to plug into the integrated models across all frequencies
- Modal damping is an approximation which assumes:
 - damping to be purely proportional to velocity (e.g., a pure viscoelastic material)
 - damping to be proportional to mass and stiffness
- In reality, damping has other non-viscoelastic sources (e.g., friction)
- The relationship between the damping of a material sample / mechanical component and the equivalent modal damping of a full built-up structure is not straightforward
- The test plan will investigate:
 - trends in as a function of temperature, strain and frequency
 - changes in as we go from a simple element rod, to a built-up structure

Multiple Sources of Crystalline Material Damping Exist

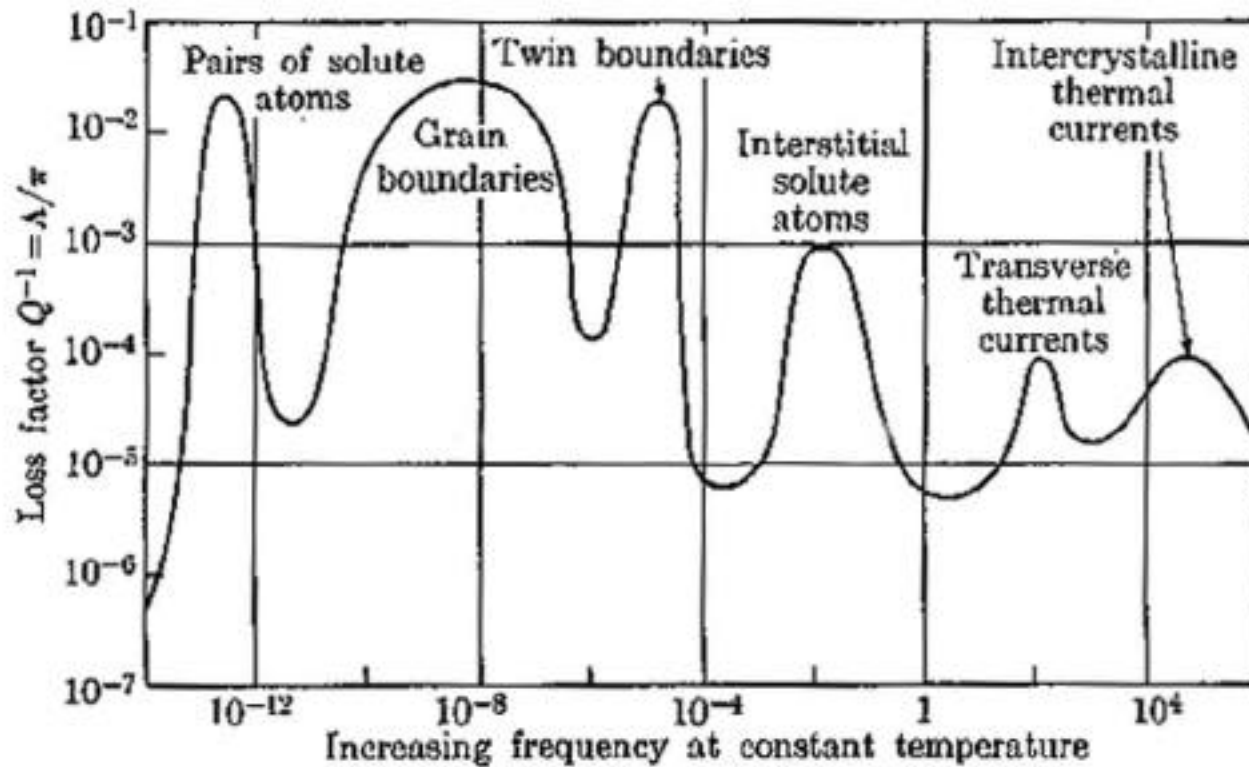
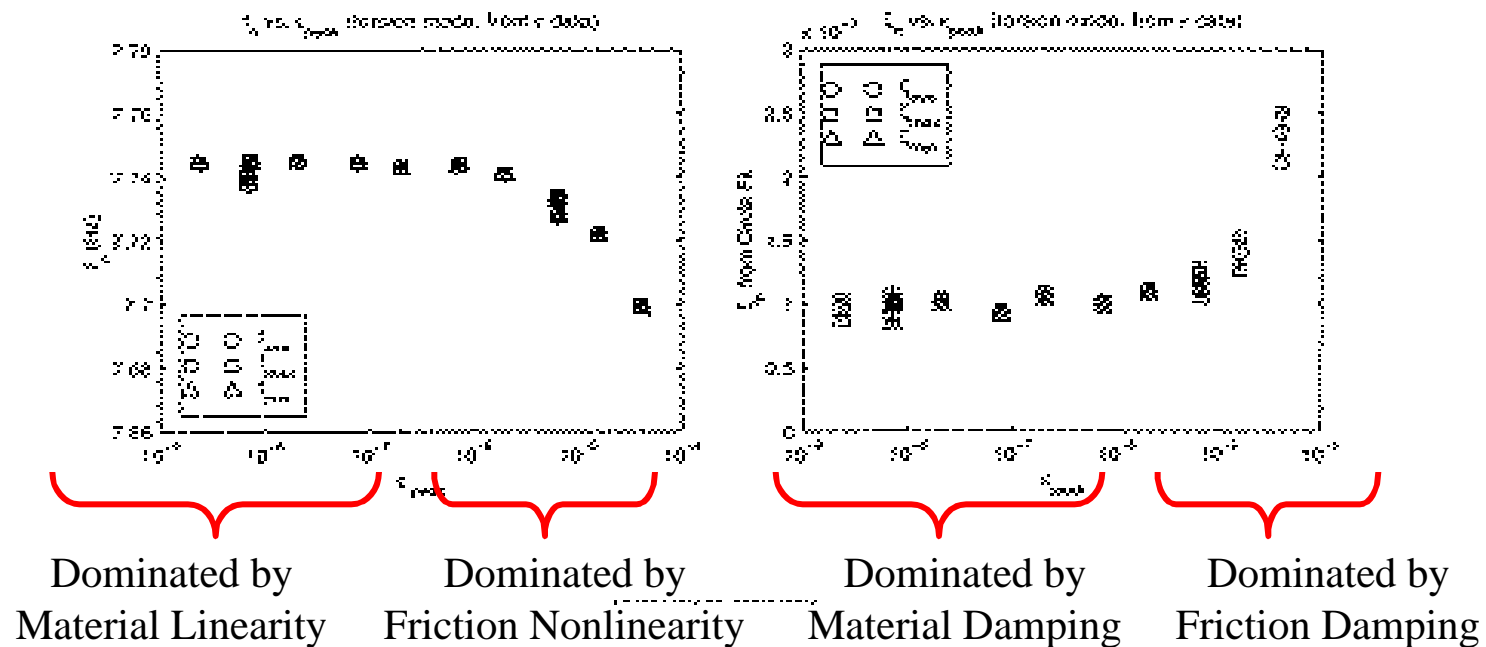


FIG. 14.3. Typical damping spectrum of a crystalline material at low stress. (After B. J. Lazan, 1959.)

(B. J. Lazan, 1959)

DATA ON DYNAMIC PROPERTIES vs. STRAIN

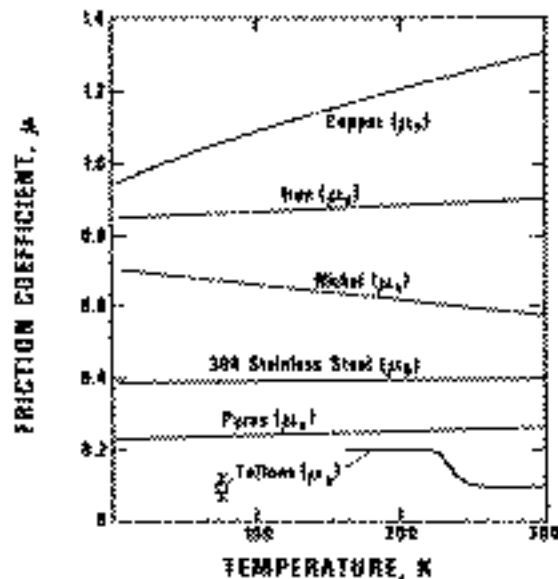


*DYNAMIC PROPERTIES ARE STRAIN DEPENDENT BUT
ASYMPTOTE BELOW MICROSTRAIN*

More data to be supplied by ROSI & CU experiments

Ref: M. D. Ingham, E.F. Crawley, and D.W. Miller, "Microdynamics and Thermal Snap Response of Deployable Space Structure", MIT Report SERC #2-98, May 1998.

DATA ON CRYOGENIC FRICTION



Conforming Interface

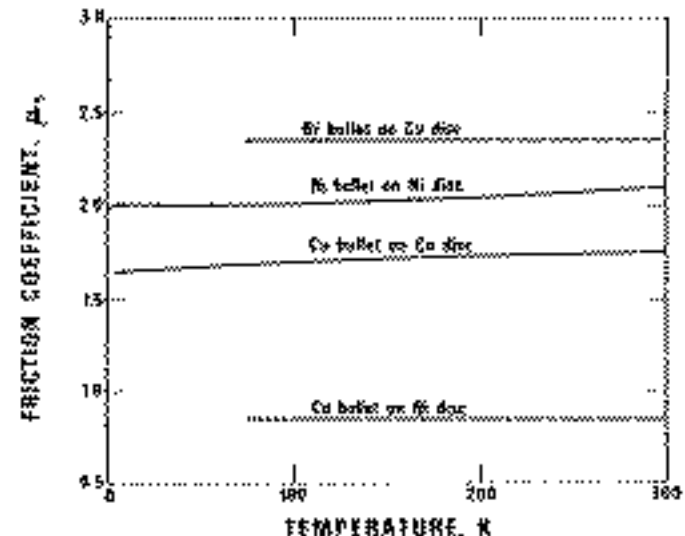


Fig. 2. Friction coefficients for nickel and copper combinations, where bullets are sliding on disks and nickel is harder than copper [12].

Non-Conforming Interface

- **COEFF. OF FRICTION IS NOT VERY SENSITIVE TO TEMP.**
- **BUT CTE MISMATCH WITHIN BUILT UP STRUCTURE WILL CHANGE APPLIED NORMAL FRICTION LOADS**

Ref: R.L. Tobler (NIST), "A Review of Antifriction Materials and Design for Cryogenic Environments",
Advances in Cryogenic Engineering Materials, Vol.26, 1981

DATA ON MATERIAL DAMPING: ALUMINUM ALLOYS

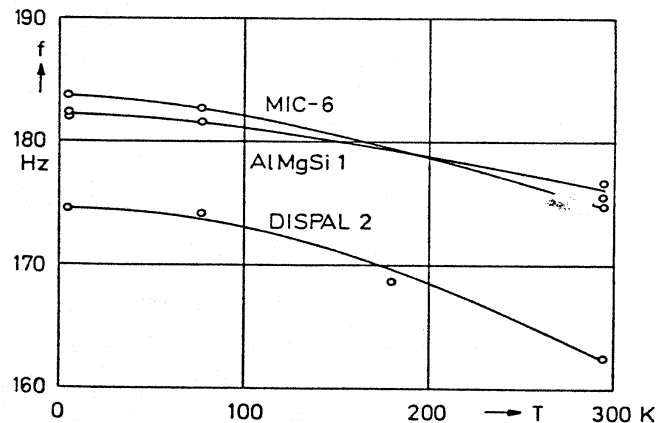


Fig. 6 Resonant frequency shift versus temperature for three alloys

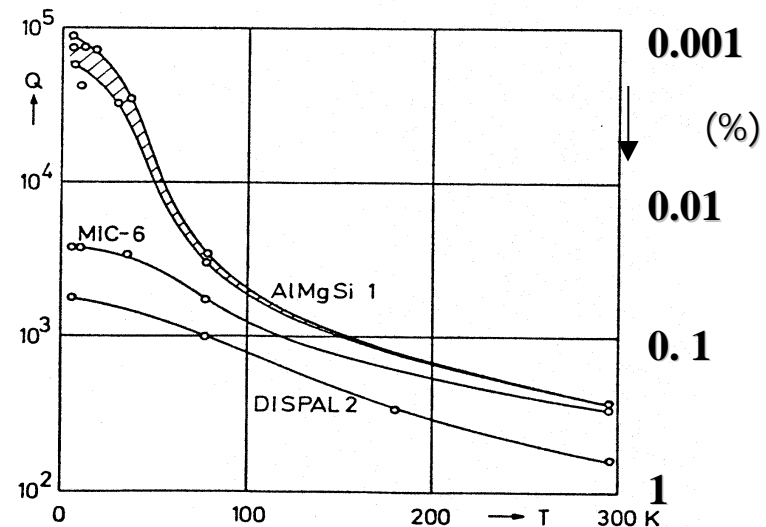


Fig. 7 Temperature dependence of quality factor Q for three alloys

- **CERTAIN ALLOYS SHOW A 1/10 DECREASE IN DAMPING AT CRYO**
- **DAMPING >0.01% AT CRYO**
- **MODAL FREQUENCY IS TEMPERATURE DEPENDENT BUT ASYMPTOTES BELOW LN2**

Ref: R.O. Katterloher, "Low Temperature Decay of Vibrational Resonance for Bars Made of DISPAL2 Sintered Al-Powder, Alloy MIC-6, and AlMgSi", Max-Planck Institute, Germany, 1986

DATA ON MATERIAL DAMPING: ALUMINUM ALLOYS (cont'd)

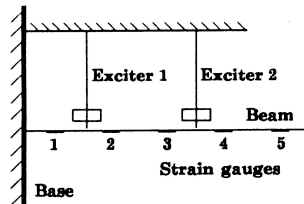


Figure 2 Simplified sketch of exciter and strain gauge measurement

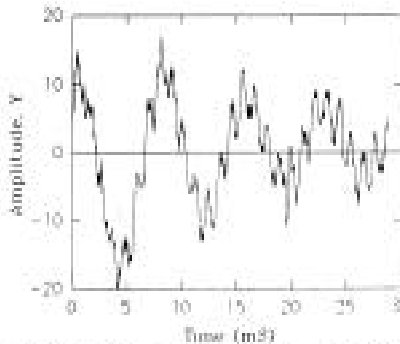


Figure 3 Time history of flexural vibration test of ELI Ti-5Al-2.5Sn at 4.2 K

Table 1 Modal characteristics of ELI Ti-5Al-2.5Sn in liquid helium temperature (4.2 K)

Mode number	1	2	3	4	5
Experimental mode (Hz)	130	620	2250	4550	7200
Theoretical mode (Hz)	130	624	2261	4470	7350
Error (%)	—	0.97	1.36	1.79	2.57
Damping ratio, ξ	0.004	0.008	0.002	—	—
Quality factor, Q	125	100	250	—	—

$$= \frac{^2ET}{2C} \frac{1}{1 + \frac{^2}{2} \frac{^2}{2}}$$

Zener Damping Model

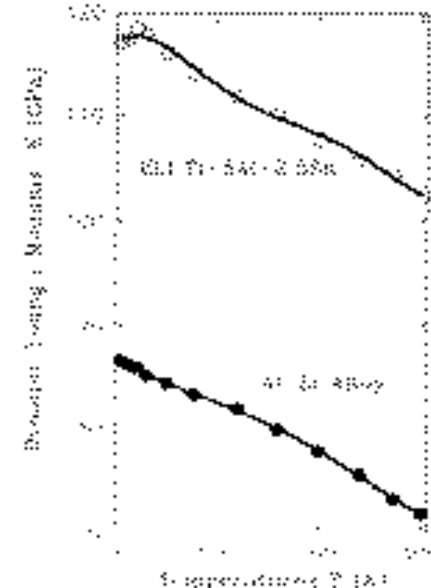


Figure 5 Temperature dependence of dynamic Young's modulus of ELI Ti-5Al-2.5Sn and Al-Li alloy between 4.2 and 300 K

- **DAMPING >0.01% AT CRYO**
- **DAMPING VARIES WITH THE MODE**
- **“E” IS INVERSELY PROPORTIONAL TO TEMPERATURE**
- **WHEN USING ZENER MODEL TO PREDICT DAMPING AT CRYO, NEED TO INCLUDE THE EFFECT OF TEMPERATURE ON OTHER PARAMETERS**

Ref: Z. Zhang et al., “Dynamic Young’s Moduli of Space Materials at Low Temperature”, *Cryogenics* Vol. 34., no. 10, Oct. 1994.

DATA ON MATERIAL DAMPING: COMPOSITES

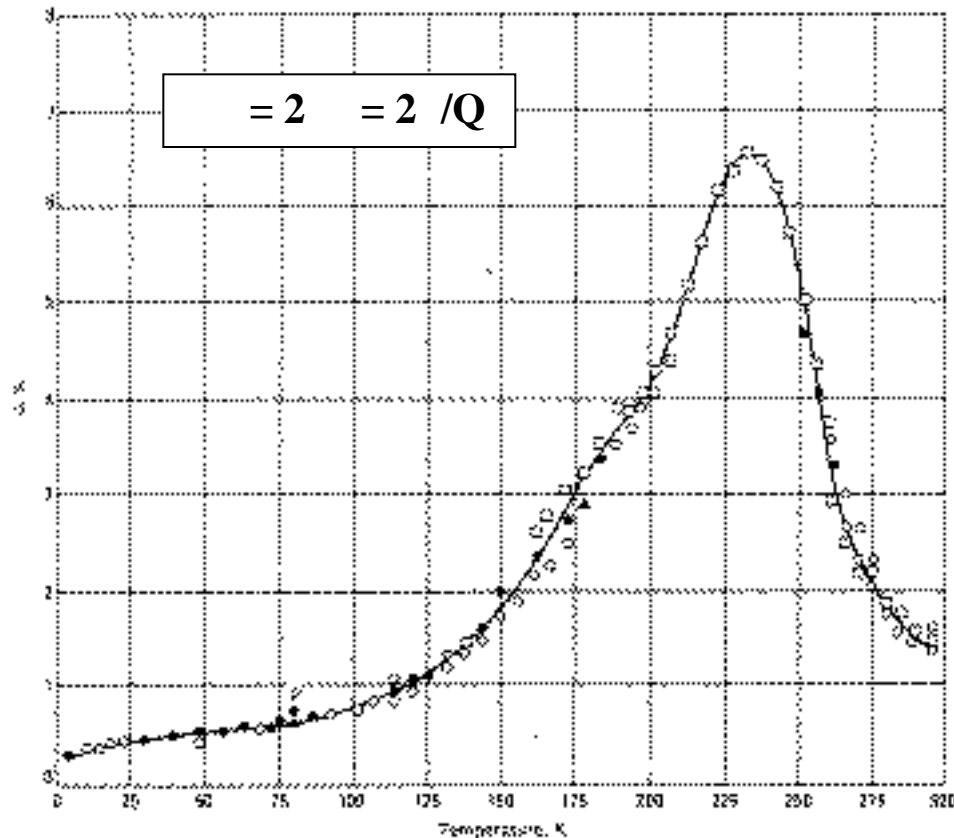


Fig. 22 Variation of specific damping capacity (Ψ) with temperature for a glass cloth-epoxy specimen

- Damping asymptotes at low temperature
- Cryo damping of glass/epoxy composite ~0.03%
- Damping a function of fiber, matrix, and orientation
- Increase in damping at “cool” temperatures due to beta relaxation - not consistent with Zener theory.
- No documentation on sample size or test procedure

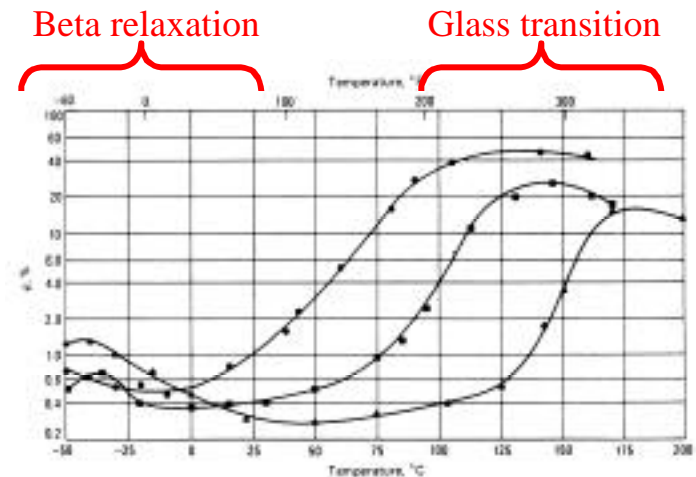


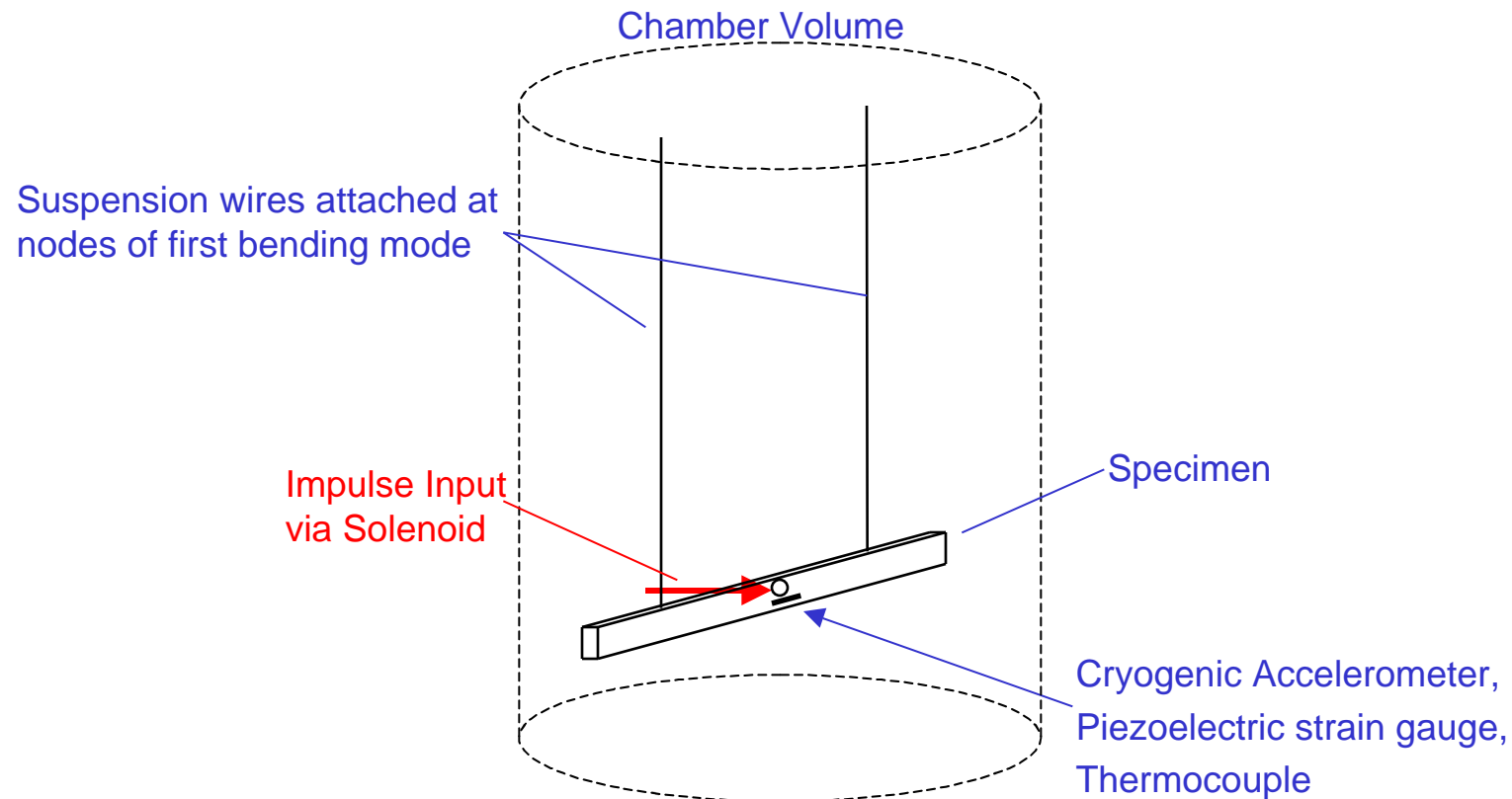
Fig. 23 Variation of specific damping capacity (Ψ) with temperature for 0° unidirectional composite made from Epikote flexibilized resin. $V_f = 0.5$

Ref: C.A. Dostal, et al, :Engineered Materials Handbook: Volume 1 - Composites”, ASM International, Metals Park, Ohio, 1990

Primary Testing Concern is Isolation

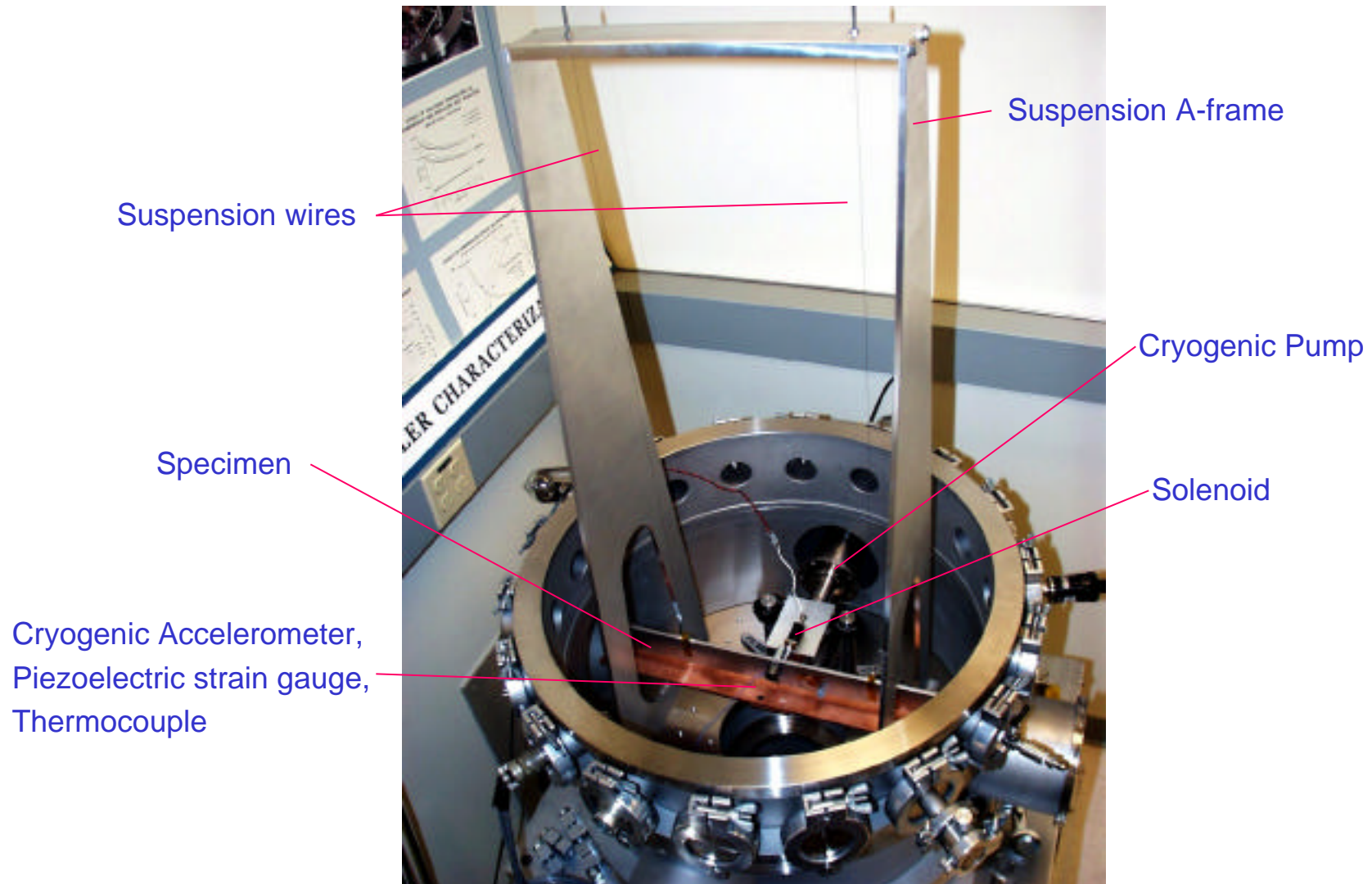
- As repeatedly mentioned in the literature, extraneous sources of damping are difficult to avoid
- Care must therefore be taken to isolate the material damping we're interested in
- Undesired damping sources include friction, aerodynamic damping, and cabling and suspension material damping
 - Friction is most easily avoided by utilizing free-free boundary conditions
 - Vacuum conditions available to remove aerodynamic effects
 - Careful design can limit cable and suspension effects

Cryogenic Material Damping Test Configuration



Fully isolated configuration will replace accelerometer and strain gauge outputs with an interferometer output to improve mechanical isolation

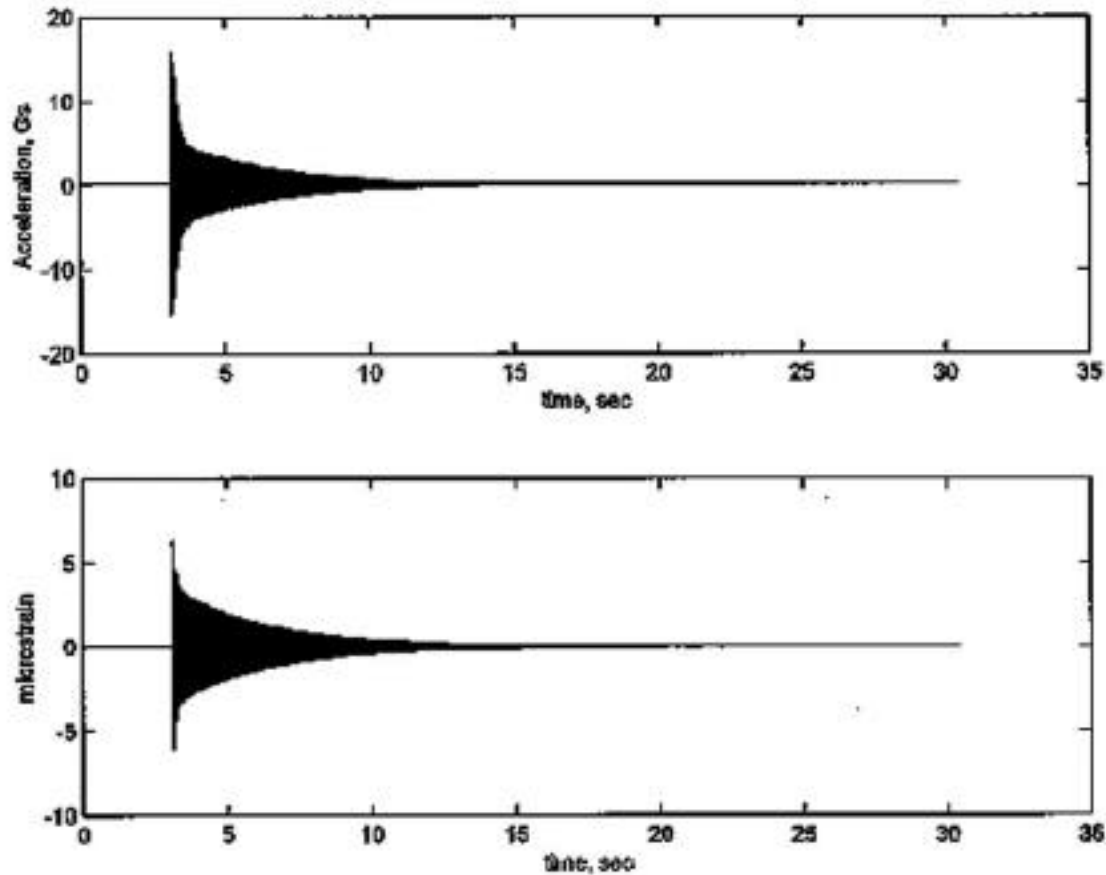
Present Test Configuration



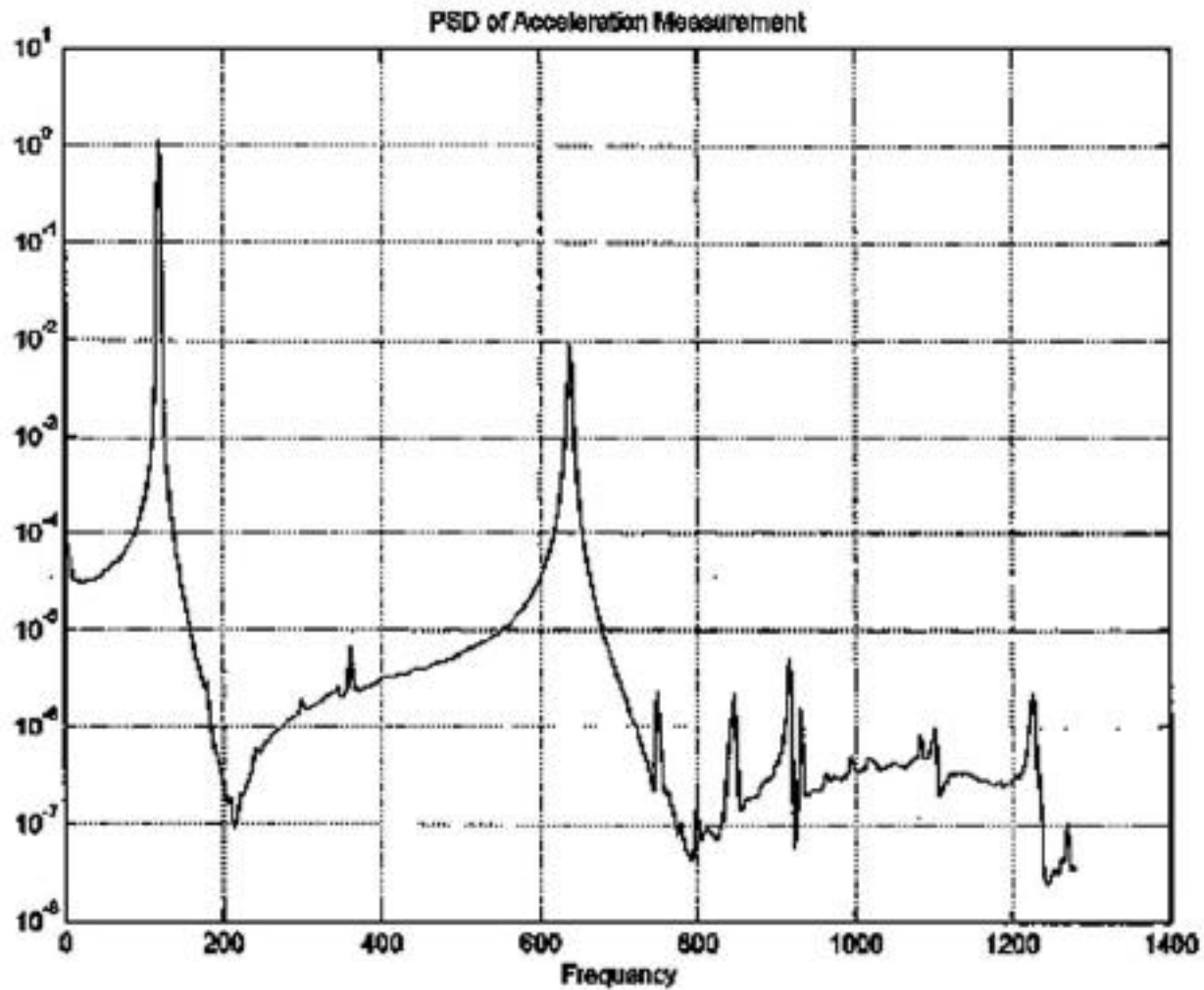
First Specimen Designed to Provide Modal Separation

- Al 6061-T6 beam - 20x2x0.25 in)
 - First bending: 178 Hz, Next natural freq.: 490 Hz
- Resolvable strain levels:
 - PCB 351 B11 accelerometer resolution: 10 mg 40 μ
 - PCB 740 M03 piezo strain gauge resolution: 0.01 μ
 - Chamber noise floor near 10 mg, specimen noise floor TBD
- Input force levels:
 - 300 g PCB accel. threshold reached at 30 lb
 - 1 lb impulse allows three order of magnitude ring-down observation by accelerometer
 - >1 lb should be available from either solenoid or piezoelectric actuators

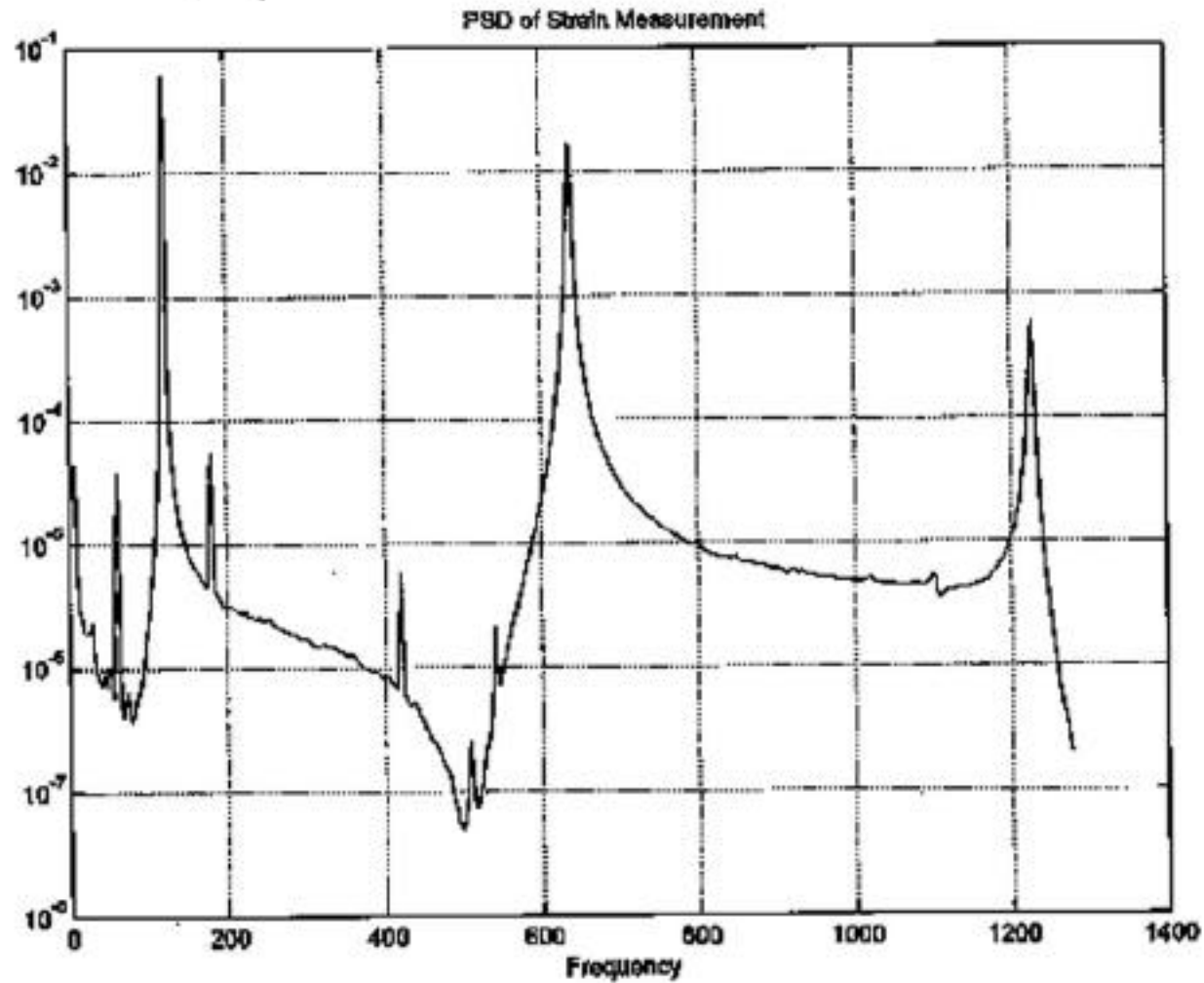
Sample Acceleration and Strain Responses at Room Temperature



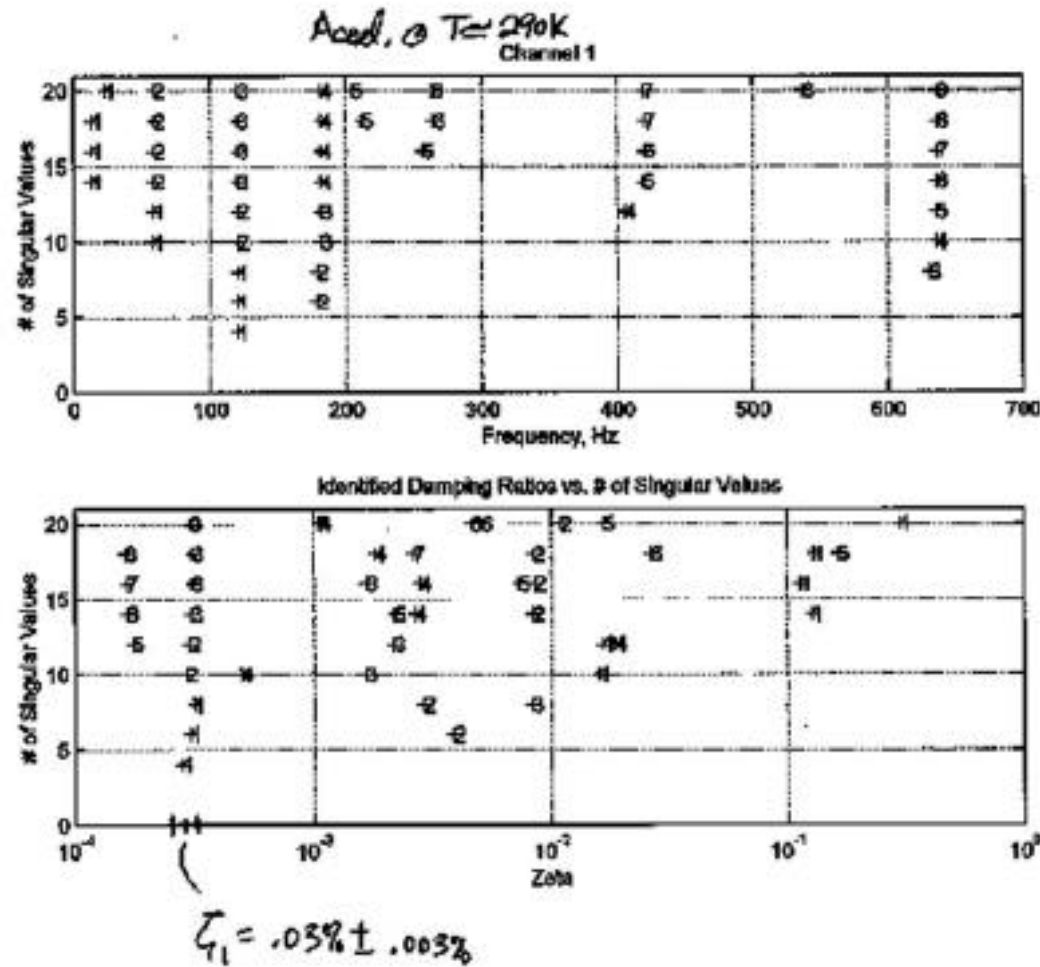
First Bending Dominates Response, but Additional Spectral Content is Significant



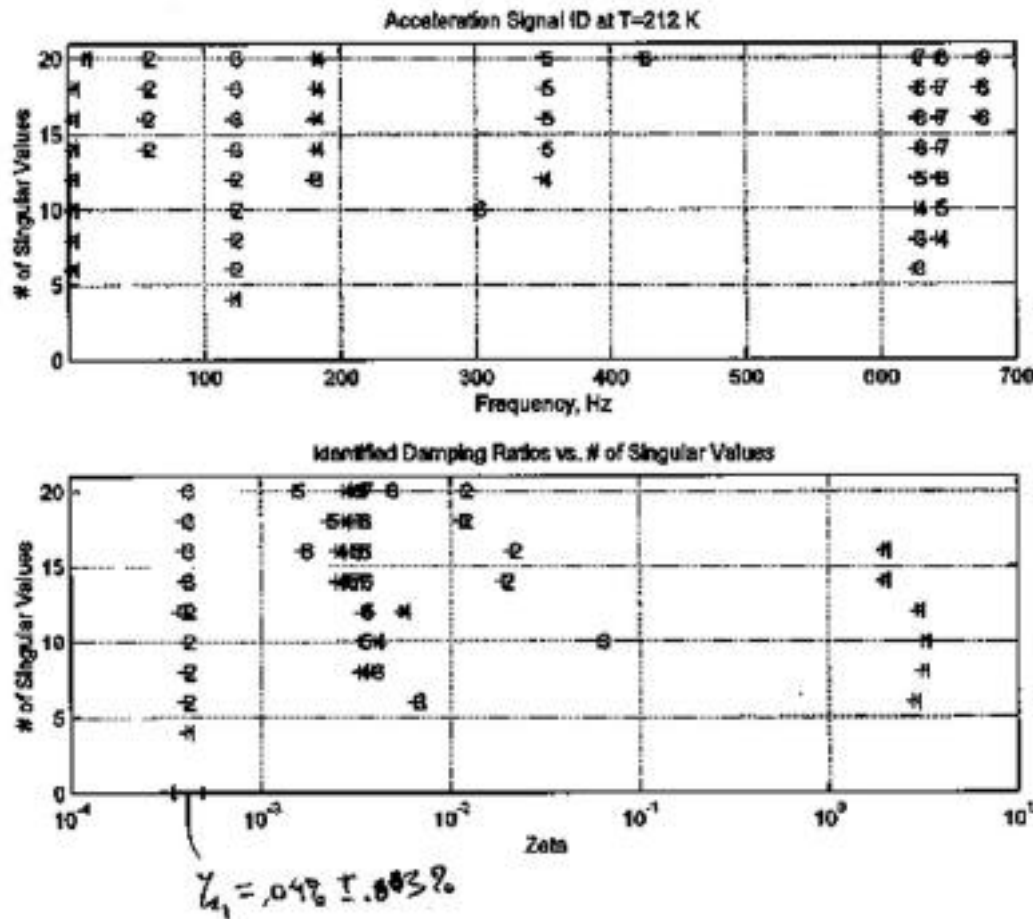
...Same for PSD of Strain Response



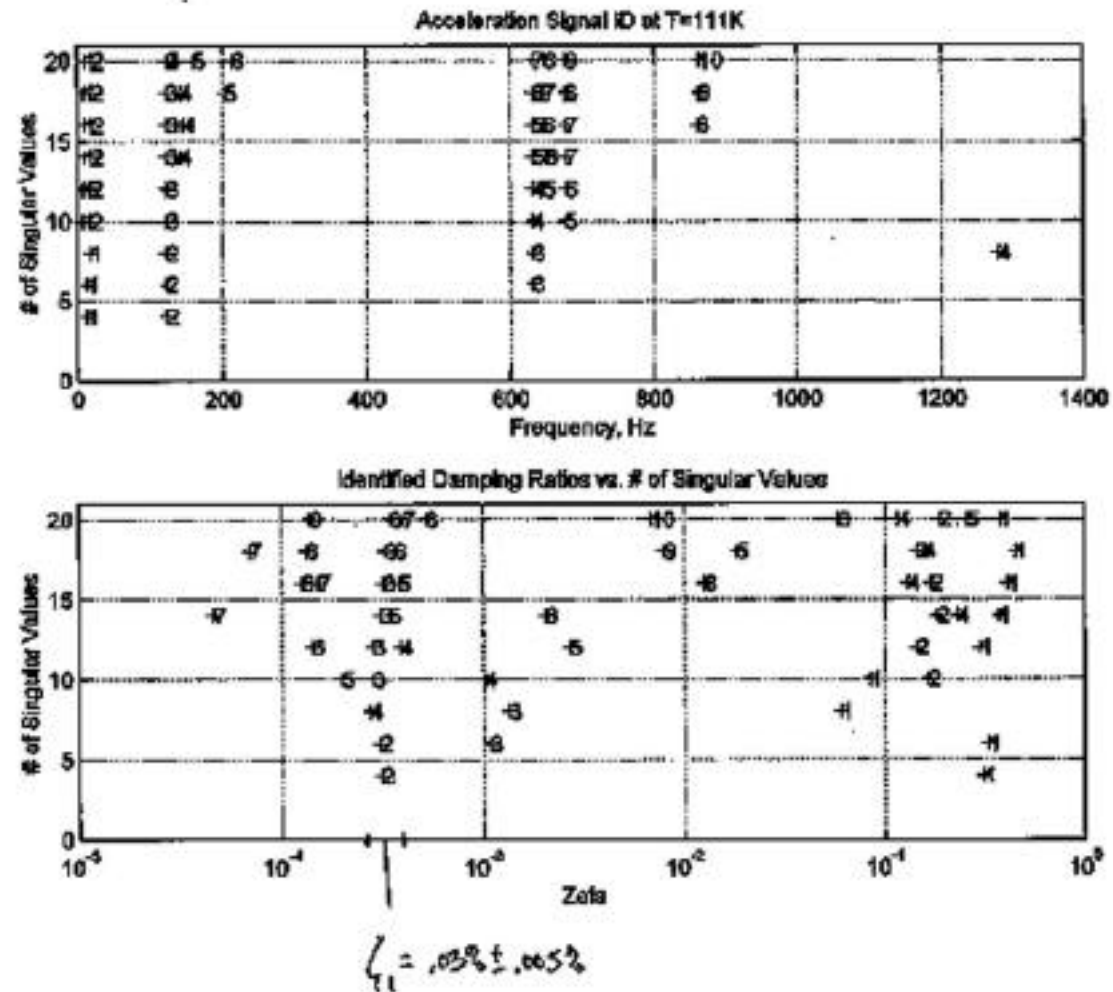
ERA was Applied to Extract Mode-Dependent Damping Estimates



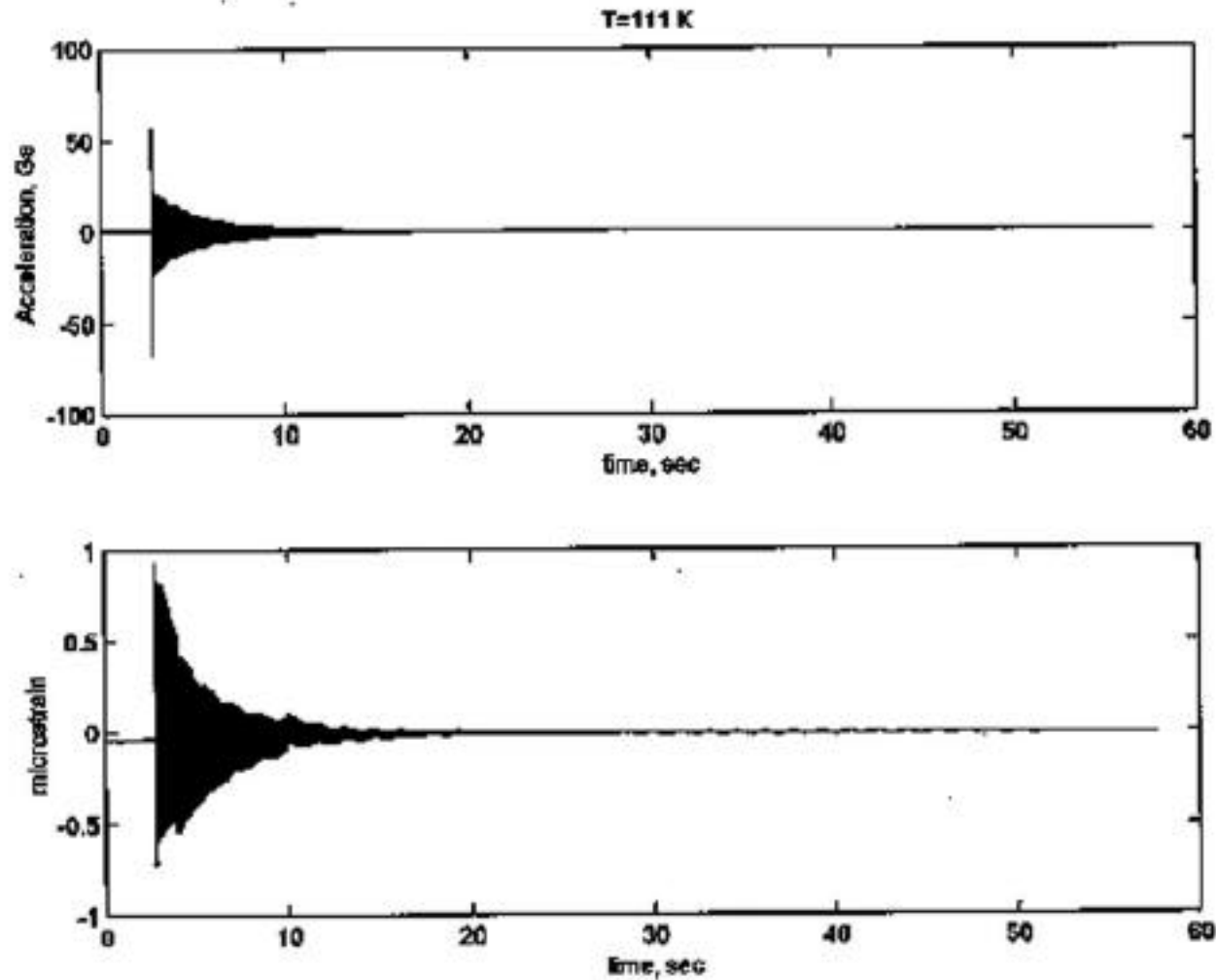
Identified Damping of First Bending Observed to Increase from T=290K to T=212K



Zeta Returned to 0.03% at T=111K



Piezoelectric Strain Gage Response Indicates Possible Delamination at T=111K



Future Work

- Complete data set with current configuration to characterize test environment and develop test methodologies
- Switch to interferometer output configuration for ideal mechanical and thermal isolation
- Add to material/frequency/stress state test matrix as motivated by NGST modeling requirements
- Consider experiments to evaluate and advance existing material damping theory
- ROSI-like mechanical test config. may be required for component/subsystem testing